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A solar still desalination system with enhanced productivity

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ABSTRACT

Increasing the productivity of solar stills has been the focus of intensive research. Many introduced developments, however, require complex components and entail notable increases in cost and land requirements. Developing a compact, productive, and easy-to-operate system is a main challenge. This paper describes a sustainable modification of the solar still that significantly enhances its productivity without forsaking its basic features. A simple amendment in the form of a slowly rotating drum is introduced allowing the formation of thin water films that evaporate rapidly and are continually renewed. The performance of this system was compared against a control without the introduced drum. Throughout the experiment, the new system gave considerably higher yield than the control with an average increase in daily productivity of 200%. Moreover, during sunshine hours, the increase in yield could surpass 6–8 times that of the control. Important parameters such as ease of handling, material availability, efficacy, low cost, safe water quality, and space conservation are maintained. One side-benefit of this design is solving stagnation problems that usually develop in conventional stills. The new simple modification in this study presents a cost-effective and efficient design to solar stills especially in areas with abundant sunshine.

Keywords: Brine; Drum; Productivity; Solar still

1. Introduction

Renewable-energy-based desalination methods offer a promising solution to both water shortage and environmental pollution problems that continue to aggravate worldwide. The solar still is one such sustainable method that has been in operation for hundreds of years, especially in arid areas. In their simplest design, solar stills consist of transparently-roofed basins that are normally black-painted to maximize solar heat absorption. Brackish or seawater is placed in the basin and slowly evaporates due to heating by the sun rays. This vapor condenses as it hits the cooler cover of the still and trickles down where it is collected by separate channels as distillate. The stills can have various forms, shapes, and cover materials and their operation requires little maintenance besides

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regularly flushing the basin to remove accumulated salts.

The major limitations on the use of solar stills, however, include their low productivity per unit installation area compared to fuel-based desalination methods, their high initial costs per production unit, the need for large installation areas, variability of the energy source, and limited experience with large-scale applications. Increasing the productivity of solar stills has therefore been the focus of intensive research. Some studies have used different heat absorbers such as gravel [1,2], sponge cubes [3–5], rubber [6,7], glass balls [8], charcoal [9,10], dyes, and inks [7,11,12] among others [13] in order to maximize heat absorption in the still basin. Other researchers experimented with solar stills that are coupled to reflectors [14–18] that concentrate solar rays, flat-plate-collectors [19–22] to further increase the temperature of the water in the basin, or to separate condensers [23–28] that are cooler than the still cover. Others used multiple-effect stills [29–36], wicks [37–39], vacuum technologies [40,41], excess solar energy storage [42,43], humidification–dehumidification processes [44–46], and computerized sun tracking device for rotating the solar still with the movement of the sun [47]. In some cases, new designs of the solar still were employed such as utilizing a transportable hemi-spherical dome-shaped still [48], using tubular stills [49], and horizontal transparent tubes instead of basins [50]. A critical literature review of various developments in solar stills has been recently presented [51]. It was noted that many of these developments increase the productivity to a limited extent while often introducing complex or expensive components that may not match the low level of expertise and infrastructure, that characterizes places with severe water stress, and that lend themselves to solar stills application. The installation of solar panels as well as of collectors, ponds, condensers, sun-tracking devices, and other productivity-enhancing devices also require considerable space and can entail notable increases in cost. The yield increase obtained by these additions in many cases does not justify the added drawbacks and therefore developing more compact and easy-to-operate systems with low cost increase is a main challenge.

The objective of this paper is to present a detailed description of a novel modification into the simple conventional solar still. The introduced modification was found to significantly increase the productivity of the still while maintaining its basic features and advantages such as compactness, sustainability, and ease of handling. The performance of the new system is compared against that of a conventional basin solar still used as a control and experimental results for the modified solar still and the control are discussed.

2. Project description

The basic principle in the new design is to expose a considerably larger amount of water to sunlight than that exposed in conventional stills. Increasing the evaporating surface increases the output of the solar distillation unit. Although some studies have addressed this fact by modifying solar stills to increase the evaporation area by using sponges, wicks, or fins, the design introduced herein is totally different and none of the previous work used a similar concept. A partly submerged slowly rotating hollow cylinder or drum is introduced into the still. As it rotates, a thin film of water is formed around its circumference (both the internal and external) and this film easily evaporates due to the high temperature of the drum, which is constructed of a cheap yet sustainable heat-absorbing material. Only a low rotational speed of the drum is needed and hence the required energy for this rotation can be provided by solar or wind energy. Fig. 1 shows a schematic of the proposed solar still design. The performance of this system is compared against a similar one without the introduced drum. Both systems have a double-sloped or triangular cover geometry. The proposed design presents a sustainable and environmental friendly development to the conventional solar still that notably enhances the productivity without forsaking other important parameters such as ease of handling, material availability, efficacy, low cost, safe water quality, and space conservation.

3. Materials and methods

Water basins for the stills were constructed of plywood 18 mm thick and coated with black fiberglass material. This material has a relatively long life expectancy, is easy to handle, and does not require any kind of insulation on the sides and bottom while rendering the basin leak-proof. Grooved edges were made in the wood at the sides, covered with fiberglass, to allow for ease of placement and removal of the covers as well as provide a tight seal at the joints. The dimensions of the still basin were 0.67m × 1.5 m, giving a unit squared meter of surface area for each still. Aluminum channels for distilled water collection were fixed in place to collect the condensed distillate. Photovoltaic panels were used to operate the motors on solar energy during sunshine hours. These panels were connected to storage batteries in order to operate the systems during the night. The current intensity

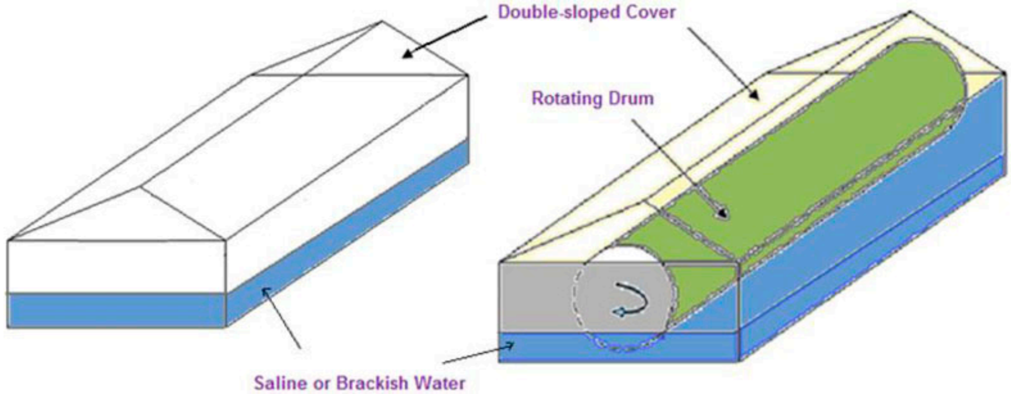

Fig. 1. Conventional solar still (left) and new system (right).

required to run one motor was 0.1 A. Aluminum sheets mill finish 3,000 × 1,500 × 1.0 mm for the drum (0.6 m diameter, 1.4 m length) were purchased and wrapped into cylinders that were then painted in black mat. Low-carbon steel shafts 20 mm diameter × 1.7 m length and mounted on 20 mm ball-bearings were used to install the drum within the solar still.

The still covers were made of plexi-glass that was cut into the required dimensions and assembled as shown in Fig. 2. Inlets to allow for basin filling, outlets connected to the aluminum channels for distillate collection as well as outlets at the bottom of the basin for brine discharge were installed and controlled with ball-type valves. Thermocouples (Type K) were installed to measure temperature at four locations for each of the experimental stills: inside and outside cover, inside still, and in the basin water. The thermocouples were attached to a board connected to a PC for continual reading of temperature. Digital scales (CPWplus) to measure the distillate water output were supplied by Adam Equipment (adamdu@adamequipment.com) and were equipped with a software that allows continual reading of the collected weights. Distillate was collected in 6-L Pyrex Erlenmeyer flasks (Fig. 3). Once all equipment became available and fixed in place, experimental data collection proceeded for the relevant parameters, which included continual recording of the weather conditions, weight of collected distillate, rotational speed of the drum, water level in the still, temperatures for the inside and outside cover as well as temperatures of the ambient air inside the still cavity, and for the water in the basins.

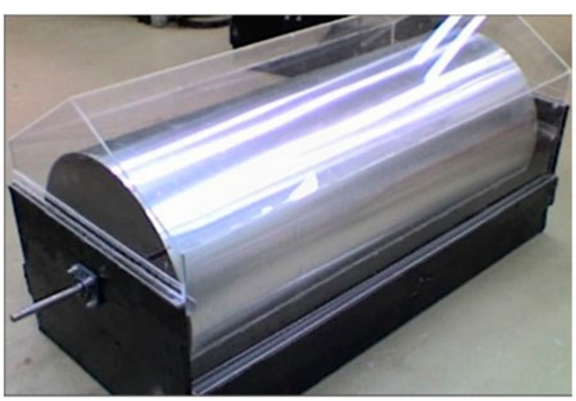

Fig. 2. Modified double-sloped (triangular) solar still during construction.

4. Performance comparison against the control still

Experimental data were collected over a period of six months starting in May and ending in October 2010. Throughout the experiment, the new system with the drum gave considerably higher yield than the control. Fig. 4 shows sample results for the productivity of the new double-sloped (triangular) system with the drum and the conventional double-sloped system, which is used as a control. It can be observed from the graph in Fig. 4 that the enhancement in productivity for a given day exceeded 200% in many cases and the percent improvement varied from month to month depending on operational and environmental parameters.

5. Discussion of experimental results

5.1. Induced productivity levels

The results shown in Fig. 4 indicate that the introduction of the drum has contributed significantly to increase the productivity of the simple solar still due to several reasons. The most important factor is

Fig. 3. Thermocouple measuring temperature within the still (top left); storage battery and speed control panel (bottom left); distillate collection flask mounted on digital scale (right).

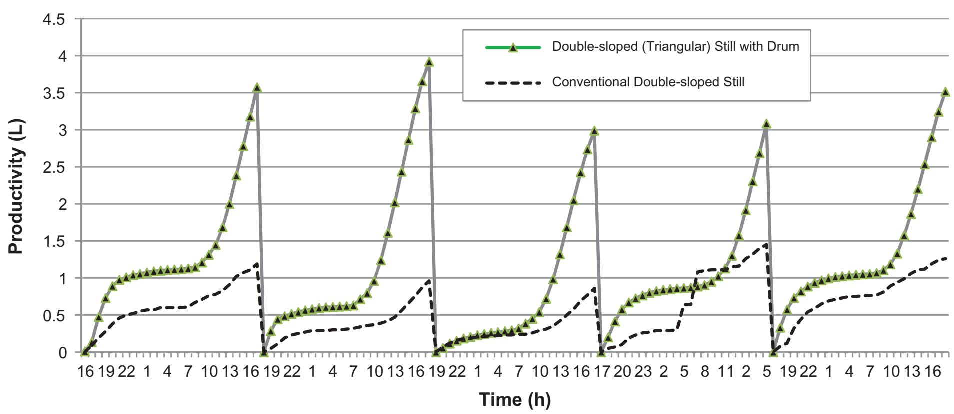

Fig. 4. Productivity of new system vs. the control.

having an increased surface area available for evaporation and the layer of water available for evaporation is thin relative to the much larger water depth in the basins of conventional stills. The effect of the rotating drum is double-sided as both the inner and outer surfaces of the drum (increasing the evaporation surface area from 1 m^2 for the conventional unit to 5.4 m^2 for the modified still) are available for the thin water film to form. This water is also subjected to a higher evaporation temperature than that in the basin due to the higher temperature of the drum itself, which is made of a high heat-absorbing material and covered by a relatively thin water film and which also receives more direct sunlight due to the particular system configuration. As shown in Fig. 5, even higher improvement rates than the ones shown in Fig. 4 are obtained if only sunshine hours are considered.

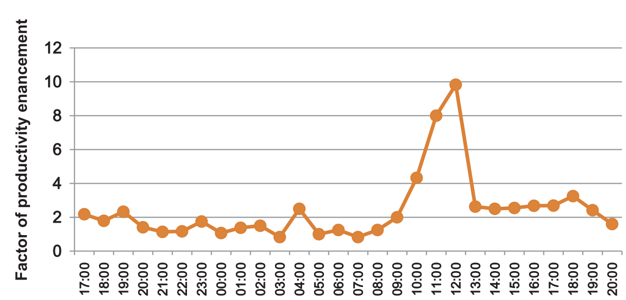

Fig. 5. Variation in productivity enhancement relative to the control system in a typical day.

In fact, during sunshine hours, the increase in yield could surpass 6–8 times that of the control. This leads to further energy saving by stopping night

Fig. 6. The shielding surface layer in the control still.

operation which contributes little to the productivity, eliminating the need for storage batteries, and inducing savings in initial costs. Moreover, the significant problem of stagnation that is present in simple solar stills is now solved: no shielding layer forms at the evaporating water surface as is the case for the control shown in Fig. 6. The growth of algae and other microflora particles on the brine surface and in the basin of simple solar stills generally reduces heat transfer to the brine [52]. The introduced drum, on the other hand, serves to continually break any clogging layers at the surface of the still water in the basin and the thin evaporating film at the drum surface is persistently renewed as it gets immersed in the basin water.

5.2. Comparative productivity results

In studying the effects of important parameters influencing the performance of solar stills, Khalifa and Hamood developed four correlations for the effects of brine depth, dyes, solar radiation, and cover tilt angle on productivity based on data from several studies. These correlations apply for passive stills with a galvanized iron body, an insulation thickness of 5–10 cm of polystyrene or other insulation with similar conductivity, glass cover with 5°–45° tilt angle, 1–10 cm brine depth, 20°–35° latitude angle, 50–100 mg/L dye concentration, and under solar radiation of 8–30 MJ/m^2/d. In order to compare with the performance of other conventional stills reported in the literature, the correlation suggested by Khalifa and Hamood, solar radiation I (MJ/m^2/day) is used to calculate the productivity as follows [53]:

$$y = 0.0036I^2 + 0.0701I + 0.2475$$

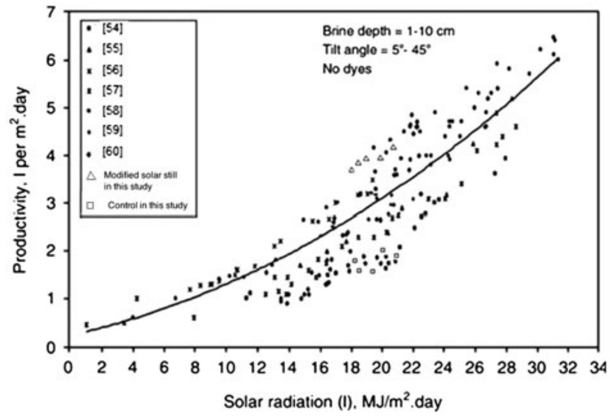

Fig. 7. Benchmarking results with values in the literature (Adopted from [53]).

where y is the productivity of the conventional solar still. The results obtained using this equation and applying the values of solar radiation for different months gave close results to the experimental values obtained for the productivity of the control system. These results are shown in Fig. 7, which is adopted from Khalifa and Hamood and modified to include the modified solar still and the control presented in this study. It is observed from Fig. 7 that the results for the conventional solar still used as a control in this study fall on the lower range of the graph, mainly due to the particular climatic and geographic conditions and also to the materials used, for example glass compared to plexi-glass covers, of the experiment conducted herein. For different weather conditions and in areas where the other studies [54–60] have been conducted, the control is expected to yield a higher productivity and accordingly the productivity of the new system would also shift upward for higher ambient temperatures and more sunshine.

5.3. Comparative cost results

The cost of the new still was estimated to vary between \$6 and 60 /m^3 of produced water depending on conditions such as interest rate, initial capital costs, productivity, and service lifetime [61,62]. This estimate compares favorably with the costs reported for solar stills in the literature and that tend to fall on the upper limit of this range [51,61].

6. Conclusion

Although enhancing the productivity of solar stills to minimize their cost has been the subject of extensive research, the success rate of many such endeavors is limited. It is crucial in enhancing the system performance to maintain its basic advantages of ease of construction, maintenance and operation, simplicity, and adaptability to low-tech regions. Many proposed developments in the literature enhance the still performance and productivity but only to a limited extent, whereas a greater enhancement often comes at the expense of simplicity in design, compactness, low-cost, low-tech, and low-labor requirements. Moreover, the increase in system productivity that is obtained in almost all cases is limited to less than 100%, often varying between 10 and 40%. Promoting solar stills thus requires focusing research efforts on improving existing technologies with minimal additional as well as with more compact installations that would reduce land use, since large space requirement is the major contributor to the high initial costs of solar stills.

The introduced modification in this study significantly increases the productivity (more than 200% on average) while preserving the key advantages of the solar still in being simple, compact, and low-tech, requiring little maintenance and entailing low additional costs. The proposed idea builds on exposing a larger amount of saline water to sunlight than that normally exposed in conventional basin stills. The slowly rotating drum introduced into the still cavity for this purpose allows a thin water film to continually form and evaporate. The drum is hollow on both of its vertical edges and hence the water film forms on both its inner and outer sides. The thin water film evaporates at a fast rate as opposed to the much deeper water brine found in the basin of conventional stills. The fast evaporation of the water film is also attributed to the high heat of the rotating drum, which receives more direct sunlight than the basin water. One side-benefit of this design is solving the stagnation problem that usually develops in conventional basin solar stills. The modified solar still with the rotating drum allows a constant renewal of the evaporating water film layer. This new system, therefore, presents a cost-effective and efficient design to solar stills especially in areas with abundant sunshine and where the cost of obtaining fresh water is high.

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References

[1] M. Sakthivel, S. Shanmugasundaram, Effect of energy storage medium (black granite gravel) on the performance of a solar still, Int. J. Energy Res. 32 (2008) 68–82.

[2] A. Nafey, M. Abdelkader, A. Abdelmotalip, A. Mabrouk, Solar still productivity enhancement, Energy Convers. Manage. 42 (2001) 1401–1408.

[3] V. Velmurugan, M. Gopalakrishnan, R. Raghu, K. Srithar, Single basin solar still with fin for enhancing productivity, Energy Convers. Manage. 49 (2008) 2602–2608.

[4] V. Velmurugan, K. Srithar, Solar stills integrated with a mini solar pond—Analytical simulation and experimental validation, Desalination 216 (2007) 232–241.

[5] A. Bassam, A. Hamzeh, M. Rababa'h, Experimental study of a solar still with sponge cubes in basin, Energy Convers. Manage. 44 (2003) 1411–1418.

[6] A. Bilal, S. Mousa, O. Omar, E. Yaser, Experimental evaluation of a single-basin solar still using different absorbing materials, Sixth Arab International Solar Energy Conference, Bahrain, 1998.

[7] B. Akash, M. Mohsen, O. Osta, Y. Elayan, Experimental evaluation of a single-basin solar still using different absorbing materials, Renewable Energy 14 (1998) 307–310.

[8] Z. Abdel-Rehim, A. Lasheen, Improving the performance of solar desalination systems, Renewable Energy 30 (2005) 1955–1971.

[9] M. Naim, M. Abd El Kawi, Non-conventional solar stills. Part 1. Non-conventional solar stills with charcoal particles as absorber medium, Desalination 153 (2003) 55–64.

[10] Ç. Tiris, M. Tiris, İ.E. Türe, Improvement of basin type solar still performance, Renewable Energy 9 (1996) 758–761.

[11] D. Dutt, A. Kumar, J. Anand, G. Tiwari, Performance of a double-basin solar still in the presence of dye, Appl. Energy 32 (1989) 207–223.

[12] S. Nijmeh, S. Odeh, B. Akash, Experimental and theoretical study of a single-basin solar sill in Jordan, Int. Commun. Heat Mass Transfer 32 (2005) 565–572.

[13] S. Abdallah, M. Abu-Khader, O. Badran, Effect of various absorbing materials on the thermal performance of solar stills, Desalination 242 (2009) 128–137.

[14] H. Tanaka, Y. Nakatake, Increase in distillate productivity by inclining the flat plate external reflector of a tilted-wick solar still in winter, Sol. Energy 83 (2009) 785–789.

[15] H. Tanaka, Y. Nakatake, One step azimuth tracking tilted-wick solar still with a vertical flat plate reflector, Desalination 235 (2009) 1–8.

[16] I. Al-Hayek, O. Badran, The effect of using different designs of solar stills on water distillation, Desalination 169 (2004) 121–127.

[17] M. Smyth, A. Strong, W. Byers, B. Norton, Performance evaluation of several passive solar stills, The European Test Center for Solar Thermal Energy, papers workshop, 2002.

[18] G. Zaki, A. Al-Turki, M. Al-Fatani, Experimental investigation on concentrator-assisted solar stills, Int. J. Sustainable Energy 11 (1992) 193–199.

[19] Y. Yadav, Analytical performance of a solar still integrated with a flat plate solar collector: Thermosiphon mode, Energy Convers. Manage. 31 (1991) 255–263.
[20] S. Rai, D. Dutt, G. Tiwari, Some experimental studies of a single basin solar still, Energy Convers. Manage. 30 (1990) 149–153.
[21] G. Tiwari, V.S.V. Bapeshwara Rao, Transient performance of a single basin solar still with water flowing over the glass cover, Desalination 49 (1984) 231–241.
[22] S. Rai, G. Tiwari, Single basin solar still coupled with flat plate collector, Energy Convers. Manage. 23 (1983) 145–149.
[23] J. de Koning, S. Thiesen, Aqua Solaris—An optimized small scale desalination system with 40 litres output per square meter based upon solar-thermal distillation, Desalination 182 (2005) 503–509.
[24] H. Fath, H. Hosny, Thermal performance of a single-sloped basin still with an inherent built-in additional condenser, Desalination 142 (2002) 19–27.
[25] H. Fath, Solar distillation: A promising alternative for water provision with free energy, simple technology and a clean environment, Desalination 116 (1998) 45–56.
[26] G. Tiwari, A. Kupfermann, S. Aggarwal, A new design for a double condensing chamber solar still, Desalination 114 (1997) 153–164.
[27] A. Fatani, G. Zaki, A. Al-Turki, Improving the yield of simple basin solar stills as assisted by passively cooled condensers, Renewable Energy 4 (1994) 377–386.
[28] M. Reddy, D.J. Chandra, H. Sehgal, S. Sabberwal, A. Bhargava, D.S. Chandra, Performance of a multiple-wick solar still with condenser, Appl. Energy 13(1) (1983) 15–21.
[29] M. Aboabboud, G. Mink, A. Kudish, Condensation heat recycle in solar stills, Proceedings of the World Congress on Engineering, vol. II, London, 2009.
[30] Y. Obikane, H. Al-Bilbisi, A detail design method of triangular cell multi-stage solar desalination still with wind effects, IDA World Congress—Atlantis, The Palm—Dubai, UAE, November 7–12, 2009.
[31] H. Al-Hinai, M. Al-Nassri, B. Jubran, Parametric investigation of a double-effect solar still in comparison with a single-effect solar still, Desalination 150 (2002) 75–83.
[32] J. Rheinländer, F. Gräter, Technologies for the desalination of typically 10 m^3 of water per day, Desalination 139 (2001) 393–397.
[33] S. Suneja, G. Tiwari, S. Rai, Parametric study of an inverted absorber double-effect solar distillation system, Desalination 109 (1997) 177–186.
[34] D. Dutt, A. Kumar, J. Anand, G. Tiwari, Improved design of a double effect solar still, Energy Convers. Manage. 34 (1993) 507–517.
[35] A. Singh, G. Tiwari, Performance study of double effect distillation in a multi-wick solar still, Energy Convers. Manage. 33 (1992) 207–214.
[36] G. Tiwari, Enhancement of daily yield in a double basin solar still, Energy Convers. Manage. 25 (1985) 49–50.
[37] B. Janarthanan, J. Chandrasekaran, S. Kumar, Evaporative heat loss and heat transfer for open- and closed-cycle systems of a floating tilted wick solar still, Desalination 180 (2005) 291–305.
[38] S.K. Shukla, V. Sorayan, Thermal modeling of solar stills: An experimental validation, Renewable Energy 30 (2005) 683–699.
[39] A. Minasian, A. Al-Karaghouli, An improved solar still: The wick-basin type, Energy Convers. Manage. 36 (1995) 213–217.
[40] S. Al-Kharabsheh, D. Yogi Goswami, Experimental study of an innovative solar water desalination system utilizing a passive vacuum technique, Sol. Energy 75 (2003) 395–401.
[41] H. Al-Hussaini, I. Smith, Enhancing of solar still productivity using vacuum technology, Energy Convers. Manage. 36(11) (1995) 1047–1051.
[42] E. Mathioulakis, V. Belessiotis, Integration of solar still in a multi-source, multi-use environment, Sol. Energy 75 (2003) 403–411.
[43] N. Rahim, Utilisation of new technique to improve the efficiency of horizontal solar desalination still, Desalination 138 (2001) 121–128.
[44] R. Sinnokrot, M. AbuArabib, A. Tamimi, Modeling of a conventional solar still with draft and humidification-dehumidification process, Proceedings of the First International Nuclear and Renewable Energy Conference (INREC10), Amman, March 21–24, 2010.
[45] S. Al-Hallaj, A Comprehensive Study of Solar Desalination with a Humidification–Dehumidification Cycle, The Middle East Desalination Research Center, Muscat, 2002.
[46] Y. Dai, H. Zhang, Experimental investigation of a solar desalination unit with humidification and dehumidification, Desalination 130 (2000) 169–175.
[47] S. Abdallah, O. Badran, Sun tracking system for productivity enhancement of solar still, Desalination 220 (2008) 669–676.
[48] B. Ismail, Design and performance of a transportable hemispherical solar still, Renewable Energy 34 (2009) 145–150.
[49] A. Ahsan, Kh.M.S. Islam, T. Fukuhara, A. Ghazali, Experimental study on evaporation, condensation and production of a new tubular solar still, Desalination 260 (2010) 172–179.
[50] M. Reali, G. Modica, Solar stills made with tubes for seawater desalting, Desalination 220 (2008) 626–632.
[51] G.M. Ayoub, L. Malaeb, Developments in solar still desalination systems: A critical review, Crit. Rev. Environ. Sci. Technol. 42 (2012) 2078–2112.
[52] M. Chaibi, A. El-Nashar, Solar thermal processes: A review of solar thermal energy technologies for water desalination, in: G. Micale et al., (Eds.), Seawater Desalination, Green Energy and Technology, Chap. 6, Springer-Verlag, Berlin, 2009, doi: 10.117/978-3-642-01150-4_6.
[53] A. Khalifa, A. Hamood, On the verification of the effect of water depth on the performance of basin type solar stills, Sol. Energy 83 (2009) 1312–1321, doi:10.1016/j.rser.2009.04.006.
[54] A. Tahir, Desalination of Salty Water by Solar Energy, MSc thesis, College of Engineering, University of Technology, Iraq, 1997.
[55] M. Zein, S. Al-Dallah, Solar Desalination Correlation with Meteorological Parameters, Physics Department, University of Bahrain, Zallaq, 1993.

[56] T. Tanaka, A. Yamashita, K. Watanabe, Experimental and analytical study of the tilted wick type solar still, Proceedings of International Solar Energy Congress, Brighton, Vol. 2 (1981) p. 1087.
[57] S. Ahmed, Study of single-effect solar still with an internal condenser, Sol. Wind Technol. 5 (1988) 637–643.
[58] P. Cooper, Digital simulation of transient solar still processes, Sol. Energy 12 (1969) 313–331.
[59] G. Zaki, T. El-Dali, M. El-Shafiey, Improved Performance of a Solar Still, Faculty of Engineering, Tripoli, Libya, 1992.
[60] H. Garg, H. Mann, Effect of climatic, operational and design parameters on the year round performance of single-sloped and double-sloped solar still under Indian arid zone conditions, Sol. Energy 18 (1976) 159–163.
[61] G.M. Ayoub, L. Malaeb, Economic feasibility of a solar still desalination system with enhanced productivity, Desalination 335 (2014) 27–32.
[62] S. Kumar, G. Tiwari, Life cycle cost analysis of single slope hybrid (PV/T) active solar still, Appl. Energy 86 (2009) 1995–2004.